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16. ABSTRACT The paper discusses a program being conducted by the U.S. Environmental Protection Agency (EPA), aimed at complete environmental assessment (EA) of the fluidized-bed combustion (FBC) of coal. It reviews the EA methodology being developed by EPA: identification of current technology and environmental background, including development of a list of 'the universe of potential pollutants;' development of environmental objectives via the Multimedia Environmental Goals (MEG) chart; comprehensive analysis of emissions from operating FBC systems; assessment of existing control technology; analysis of environmental control alternatives, using a Source Analysis Model (SAM) approach; and identification of further data and technology needs. It discusses the early status of applying each methodology step for the EA of FBC. It reviews EPA's ultimate goal of supporting environmental standards for FBC. It describes briefly the status of FBC technology.

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environmental assessment of the fluidized-bed combustion of coal: methodology and initial results

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In parallel with efforts in the United States to develop new energy technologies, the U. S. Environmental Protection Agency is conducting a program of environmental assessment of the developing technologies. The results of the environmental assessment effort are used to design a program for environmental control technology development. The conduct of the environmental assessment/control technology development simultaneously with the development of the energy technology itself should lead to early identification of any potential environmental problems associated with the energy technology, and to most cost effective and timely development of any necessary control technology.

One promising new energy technology under development is fluidized-bed combustion (FBC) of coal. In this paper, the main elements of the EPA program of environmental assessment of the FBC process are discussed, along with efforts to develop the basic methodology of conducting environmental assessments. Some of the key steps of the FBC assessment which are described include: (1) identification of current process/environmental background, including development of a list of potential pollutants; (2) development of environmental objectives, including preliminary prioritization of pollutants and development of multimedia environmental goals; (3) comprehensive analysis of emissions from FBC units; (4) assessment of available control technology; (5) analysis of environmental alternatives, mainly by use of source analysis models; and (6) identification of further data and control technology needs.

COVER PHOTO: Spent limestone bed material is drawn off the Babcock & Wilcox 3 ft × 3 ft Fluidized-Bed Combustor during tests at the firm's Alliance Research Center. Tapping off the hot solids provides optimum bed height and operating conditions. Particles are later tested for sulfur absorption and carbon content. B&W makes the spent material available to the U. S. Agriculture Department for analysis as a fertilizer. The Department of Transportation has also evaluated samples for use as construction and road bed material.

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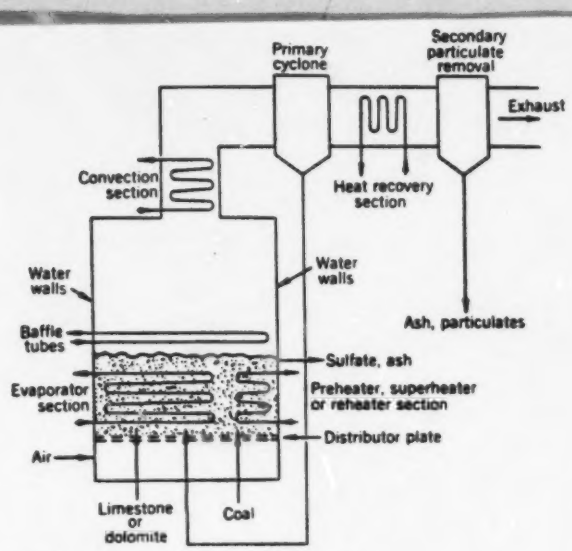


Figure 1. Fluidized-bed combustion boiler.

Increasing the use of coal, our largest single fossil energy resource, is one solution to the pressing energy problem we now face. In the coming decades, coal will provide more of our thermal energy needs as gas and oil will be considered precious industrial raw materials rather than fuels. Various new coal-based energy technologies are currently under development; one of these is fluidized-bed combustion (FBC), which offers potential for efficient and environmentally acceptable utilization of the nation's coal reserves. Significant literature exists on FBC research conducted since 1955 in Europe and in the U.S.[1-5] Briefly, FBC involves combustion of coal (or any fuel) in a bed of granular non-combustible material fluidized with the combustion air. The bed temperatures are about 1700° F (927° C); the bed consists of ash and sulfur-capturing sorbents, such as naturally occurring dolomites and limestones. Both atmospheric FBC, which is now receiving more attention, and pressurized (up to 10 atmospheres, or 1013 k Pa) FBC are under development. A FBC system is shown schematically in Figure 1.

Among the new coal-based energy technologies - including gasification, liquefaction, and coal cleaning - FBC is emerging as a potentially practical, economically viable, and environmentally acceptable method for both industrial steam production and central electric power generation. FBC appears competitive in comparison with conventional boilers using flue gas desulfurization processes. Although fluidization itself dates back to the 1920's, fluidized bed combustion of coal for steam and power generation is relatively new. Interest in its development is worldwide.

In the U.S., principal responsibility for the government effort to develop FBC is assigned to the U.S. Department of Energy (DOE). In parallel with the DOE program to develop the energy technology, the U.S. Environmental Protection Agency (EPA) is conducting a coordinated program of environmental assessment (EA) and control technology development (CTD) to assure that any potential environmental problems are identified and adequately addressed.[6] Conducting the environmental characterization in parallel with the process development program increases the likelihood of early detection and control, at a minimum cost, of any potential environmental problems that might result during the commercial application of FBC.

Some of the results of the FBC/EA program are presented, along with the initial approaches utilized in overcoming the lack of hard data on FBC emissions and on the health and

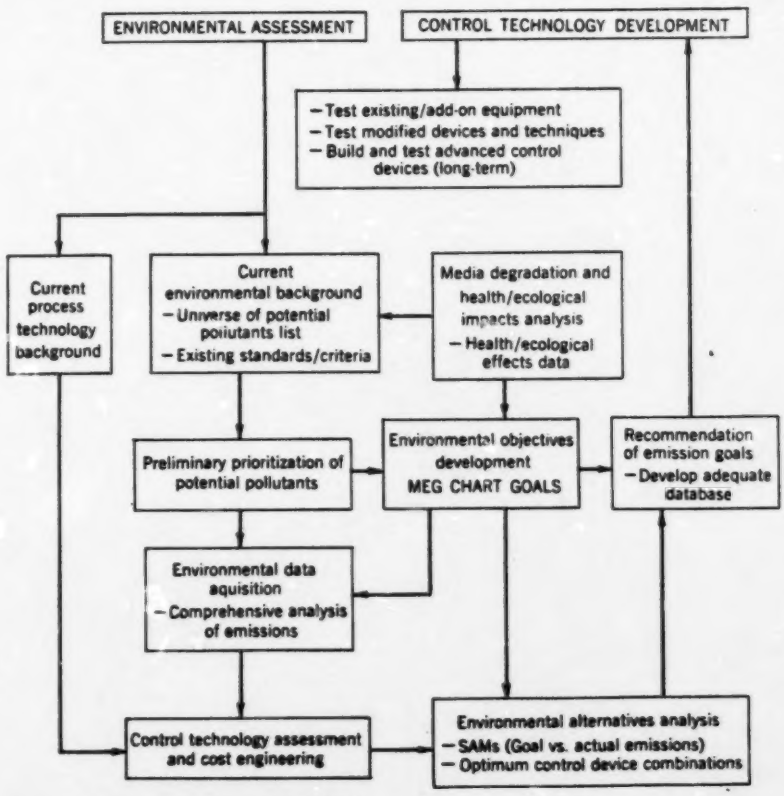

ENVIRONMENTAL ASSESSMENT
CONTROL TECHNOLOGY DEVELOPMENT
– Test existing/add-on equipment
– Test modified devices and techniques
– Build and test advanced control devices (long-term)
Current process technology background
Current environmental background
– Universe of potential pollutants list
– Existing standards/criteria
Media degradation and health/ecological impacts analysis
– Health/ecological effects data
Preliminary prioritization of potential pollutants
Environmental objectives development
MEG CHART GOALS
Recommendation of emission goals
– Develop adequate database
Environmental data aquisition
– Comprehensive analysis of emissions
Control technology assessment and cost engineering
Environmental alternatives analysis
– SAMs (Goal vs. actual emissions)
– Optimum control device combinations

Figure 2. Steps in environmental assessment.

ecological effects needed for assessment of their impact on the air, water, and land environment. The lack of hard data continues to be the major problem in providing a complete environmental assessment and efforts to overcome this situation are under way.

Elements of the FBC Environmental Assessment/Control Technology Development Program

The objective of the EA effort is to determine the environmental impact of the FBC process, and the degree of control necessary to maintain that impact at an environmentally acceptable level. The key components of the EA procedure are: first, environmental goals are established, independent of the process, based ultimately on health and ecological effects of possible pollutants; second, comprehensive analyses of emissions from existing FBC units are conducted to determine actual emissions; and third, by comparing the goals with the actual emissions, the required degree of control technology is identified, and a CTD program is designed to develop the control technology necessary to meet the environmental goals. Battelle's Columbus Laboratories is the EPA contractor responsible for carrying out the EA effort for FBC.

The EA strategy is divided into six steps. Briefly, these steps are:

1. Identification of current process and environmental background including a study of process flowsheets, status, and schedules; identification of possible emission sources within the process; projection of possible emissions by means of theoretical calculations and engineering considerations; listing of potential pollutants; collection of health/ecological effects, transformation/transport, and related information for potential pollutants.
2. Development of environmental objectives based ultimately on health and ecological effects of possible pollutants, and expressing the goals in terms of acceptable emissions. Based upon the effects, pollutants are prioritized. The goals depend upon health/ecological effects, not on the process.
3. Comprehensive analysis of emissions from existing FBC facilities. An 3. Comprehensive analysis of emissions from existing FBC facilities. An analytical approach in stages is employed to determine, in the most cost effective manner, which of the pollutants on the listing of potential pollutants are being emitted to all media from all process streams, and at what levels.
4. Assessment of available control technology, including identification of specific control technologies, evaluation of the cost of alternative degrees of control, and assessment of the environmental impact of the control process itself.
5. Analysis of environmental alternatives, to identify the optimum combination of control devices (for all pollutants and process streams), considering the trade-offs between cost and degree of control.
6. Identification of further data and technology needs, including recommendation of a control technology development program, and also indicating requirements for further health/ecological effects data, transport/transformation data, and emissions data.

The types of control technology considered may include: pretreatment of input streams (e.g., precalcination of SO_2 sorbent to improve sorbent utilization and thus reduce solid residue generation); modification of process operating conditions; modification of process design conditions for the purpose of environmental control; application of add-on control devices (e.g., devices for particulate control, and sorbent regenerators to reduce solid residue); and means for reducing the environmental impact of disposed solid residue.

Figure 2 shows schematically the relationship between the component steps of environmental assessment, and illustrates how the control technology development effort relates to the environmental assessment.

Environmental Assessment Methodology

The key tasks currently under way as part of the FBC/EA activity at Battelle are described below, and their status is summarized. Specifically, the following EA steps are discussed:

Step 1 Identification of current technology and environmental background including development of "the universe of potential pollutants."

Step 2 Development of environmental objectives via the Multimedia Environmental Goals (MEG)[7] Chart, which is preceded by preliminary pollutant prioritization.

Step 3 Comprehensive analysis of emissions from operating FBC units.

Step 4 Assessment of existing control technology based on emission stream composition results from Steps 1 and 3.

Step 5 Analysis of environmental control alternatives, using Source Analysis Models (SAM).

Step 6 Identification of further data and technology needs, including review of logical aspects of design of a control technology development program.

The "Universe of Potential Pollutants"

Since coal and sorbents contain about 60 elements (Table I), and many anions such as chlorides and sulfates are present in the combustor, the number of potential pollutants that can conceivably be formed in FBC systems (or any fossil fuel-based energy process) is vast. Specifically, numerous trace elements and compounds can be emitted. However, the need exists to limit the number of potentially polluting trace species selected for detailed study. Efforts to fulfill this need have resulted in a list of the Universe of Potential Pollutants (UOPP). The list currently includes a total of 1093 substances. Basically, the UOPP list was developed by including: (1) those elements/compounds present in the feed streams, (2) those substances known to be emitted from coal combustion/conversion processes, and (3) those predicted to have a potential for being formed, and for which threshold limit value (TLV) or other toxicity data are available. Still, the list is too large to permit detailed analysis of every substance and to determine which are indeed present in process streams. Studies are in progress to prioritize this list of substances on the basis of preliminary assessment of their relative health hazard, and prepare prioritized classes of substances requiring further study.

Recent studies[8] appear to have firmed up the role of trace metals in cancer. Also, several of the trace organic compounds which can be conceivably formed in FBC or other coal-based processes have carcinogenic potential. Systematic evaluation to determine the potential increased health hazard of these emissions is necessary. The development of the UOPP list is the first step in systematic screening.

Preliminary Prioritization of Pollutants

Substances in the UOPP list were screened to prioritize them. In the preliminary screening technique shown in Figure 3, available health-related data (threshold limit values or TLV's, and lethal dose concentrations, or LD_{50}) were used to calculate the estimated permissible concentrations (EPC) in air and water for each substance, using methods described by Handy and Schindler.[9]

These methods employ a simplified approach to estimate—for preliminary planning purposes only—the maximum permissible ambient concentrations of pollutants for continuous exposure, based upon available TLV and LD_{50} data. The EPC were compared with worst case calculated ambient ground level concentrations (GLC) for air, and stream water concentrations (SWC) for water, for each substance. The GLC and SWC values were calculated from the maximum possible emission of each substance assuming that it is totally discharged from the FBC process to either air or water medium. For example, the GLC for nickel chloride was calculated by assuming: that all of the nickel and all of the chlorine present in the coal and sorbent feed to the combustor combined to form $NiCl_2$ in the flue gas; that ts $NiCl_2$ was emitted without any control; and that the stack emissions were diluted according to a selected dispersion model to give the GLC. This can be construed as a worst case, first step in prioritization effort. If the ratio GLC/EPC or the SWC/EPC was greater than 1 for any substance, it was classed as Priority I, indicating justification for further study. Priority I substances include also those for which no health-related data are currently available; hence further study would be needed.

Table I. Composite analysis of elements in coal and sorbents (μg/g).

Element	Coal	Limestone
Aluminum	12900.00	3998.49
Antimony	1.30	2.70
Arsenic	5.00	2.00
Barium	130.00	100.00
Beryllium	1.60	0.80
Bismuth	0.10	0.00
Boron	102.00	18.00
Bromine	15.00	5.00
Cadmium	2.50	1.00
Calcium	6780.00	374053.62
Carbon	750000.00	113711.95
Cerium	11.00	0.00
Cesium	1.00	0.00
Chlorine	1400.00	55.00
Chromium	20.00	11.00
Cobalt	9.60	100.00
Copper	15.00	47.00
Dysprosium	1.00	0.00
Europium	0.20	0.00
Fluorine	61.00	230.00
Gallium	3.10	0.00
Germanium	6.60	0.30
Hafnium	0.97	0.00
Indium	0.04	0.00
Iodine	2.78	0.00
Iron	21300.00	4295.92
Lanthanum	6.90	1.60
Lead	34.80	30.00
Lithium	25.00	0.00
Magnesium	500.00	3269.60
Manganese	25.00	500.00
Mercury	1.20	0.08
Molybdenum	7.50	37.00
Neodymium	6.40	0.00
Nickel	21.10	75.00
Nitrogen	13800.00	0.00
Phosphorus	71.10	187.00
Potassium	2300.00	1600.55
Praseodymium	76.00	0.00
Rhodium	290.00	0.00
Rubidium	14.00	0.00
Scandium	5.20	0.00
Selenium	2.10	0.32
Silicon	30300.00	12713.88
Silver	0.20	0.00
Sodium	1800.00	699.57
Strontium	200.00	490.00
Sulfur	43000.00	0.00
Tantalum	0.40	0.00
Tellurium	0.30	0.00
Terbium	0.23	0.00
Thorium	2.00	0.00
Tin	4.80	40.00
Titanium	700.00	399.27
Tungsten	1.90	0.00
Uranium	1.60	0.00
Vanadium	32.70	16.80
Ytterbium	0.55	0.00
Zinc	272.30	30.00
Zirconium	180.00	25.50

This method was applied to the stoichiometrically calculated emissions of 241 substances (a subset from the UOPP list and consisting of 72 elements and 169 compounds, including 41 organics) from a hypothetical 220 MWe FBC power plant. The 241 substances were selected as those most likely to be present in FBC emissions (based upon available data and on thermodynamic predictions), and those which would appear to offer the most serious environmental problem (based upon TLV and carcinogenicity data). According to the preliminary results, of the 241 substances, 148 were Priority I from the water pollution aspect and 205 were Priority I from the air pollution aspect. Furthermore, since all the 148 Priority I substances for water were also Priority I for air, a minimum of 148 substances need further evaluation for control-technology needs for future FBC plants. Sample results presented in Table II show that some suspected carcinogens (Be, Co, Cr, Pb, Mn, Ni, and Ag) may be a health hazard when dispersed in air but may not be in water.

It is emphasized that these results are for preliminary planning purposes only since the TLV and LD_{50}-based models are simplistic and the estimates employ a worst-case procedure. Hence, the results are only an aid in reducing the number of substances to be evaluated, and are not conclusive by any means.

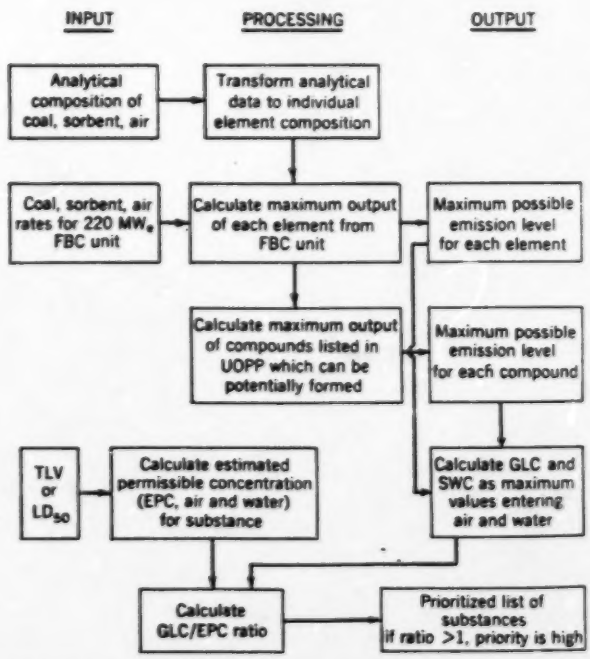

INPUT
PROCESSING
OUTPUT
Analytical composition of coal, sorbent, air
Transform analytical data to individual element composition
Coal, sorbent, air rates for 220 MWe FBC unit
Calculate maximum output of each element from FBC unit
Maximum possible emission level for each element
Calculate maximum output of compounds listed in UOPP which can be potentially formed
Maximum possible emission level for each compound
TLV or LD50
Calculate estimated permissible concentration (EPC, air and water) for substance
Calculate GLC and SWC as maximum values entering air and water
Calculate GLC/EPC ratio
Prioritized list of substances if ratio >1, priority is high

Figure 3. Steps in the preliminary screening methodology for prioritization of substances.

Table II. List of Priority I (GLC/EPC >1) substances which are also suspected carcinogens. (Preliminary results).

Substance	Air medium (GLC/EPC)[a]	Water medium (SWC/EPC)
Beryllium	59	2
Chromium	3	<1[b]
Cobalt	36	1
Lead	20	<1
Manganese	3	<1
Nickel	3	<1
Nickel chloride[c]	83	3
Nickel sulfate[d]	91	4
Silver	1	<1

[a] The numbers in the Table are ratios of the ground level or stream water concentration to the estimated permissable concentration.
[b] When the SWC/EPC <1, the substance may not be a hazard from the water pollution aspect.
[c] Assumes all Ni and Cl present in the coal and sorbent feed combine to form $NiCl_2$.
[d] Assumes all Ni and S in the coal and sorbent feed combine to form $NiSO_4$.

As the environmental assessment effort continues, the EPC values will be refined and expanded to include more rigorous health and ecological effects data (in addition to TLV's and LD_{50}'s); the models for calculating EPC will be refined, and other factors will be considered (e.g., persistence and pervasiveness of pollutants, and synergisms and antagonisms between pollutants). Also, as emissions data become available from comprehensive analyses on existing FBC facilities, more refined GLC and SWC values can be determined.

The ongoing effort to derive better EPC values, and to develop environmental goals, is discussed in the following section.

Multimedia Environmental Goals

The primary vehicle being utilized to develop environmental goals systematically is the Multimedia Environmental Goals (MEG) chart. See Figure 4.

Basically, the MEG Chart is a format for presentation of the data necessary to enable the goals to be derived. Columns IA and IB are process-specific emission goals based on current and revised emission standards, and on existing and developing technology. Columns II, III and IV are process-independent ambient-level goals (EPC) based (respectively) on: current or proposed ambient standards; toxicity considerations (where ambient standards do not exist); and mutagenic/carcinogenic/teratogenic considerations (in which case a "permissible" concentration must be estimated on the basis of acceptable risk rather than on the basis of zero, or minimal effect). In Columns II, III and IV, EPC's are presented both from the standpoint of human health, and from the standpoint of ecological effects (plants, other animals). As in the case of the preliminary prioritization of pollutants discussed previously, the types of models used to calculate EPC for Columns IIIA and IV, based on TLV, LD_{50} and other available data, are suggested by Handy and Schindler;[9] the EPC in IIIB

Multimedia Environmental Goals[a] for BENZENE.

	Emission-Level Goals					Ambient-Level Goals				
	I					II		III		IV
	Best Technology		Based on Ambient Factors			Current or Proposed Ambient Standards or Criteria		Toxicity-Based Est. of Permissable Concentration (EPC)[g]		Threshold Limit-Based EPC (for Carcinogen, etc)[a,h]
	A	B	C		D	A	B	A	B	
Media	Existing Tech. NSPS, BPT[b]	Developing Tech. BAT[b] Revised NSPS	Derived from Ambient-Level Goals (Cols II, III, IV) Based on Health Effects[c]	Based on Ecol. Effects[d]	Elimination of Discharge (EOD) Natural Background[e]	Based on Health Effects	Based on Ecological Effects	Based on Health Effects	Based on Ecological Effects[f]	Based on Health Effects
Air, $\mu g/m^3$ (ppm vol)			67,000		54			71 (.024)		67
Water, mg/l (ppm wt)			414,000	500,000				414	500	1000
Land, $\mu g/g$ (ppm wt)										

[a] The MEG Goals are intended for broad planning purposes only and are not rigorous, absolute indicators of acceptable pollutant levels.
[b] BPT = Best Practical Control Technology; NSPS = New Source Performance Standards; BAT = Best Available Control Technology.
[c] Calculated by multiplying Column II A, or the lower value in III A and IV, by a selected dilution factor. The dilution factor selected for this example was 1000.
[d] Calculated by multiplying Column II B or Column III B by the assumed dilution factor.
[e] Calculated by multiplying natural background by assumed dilution factor.
[f] Where data are available on more than one plant or animal species, the data for the most sensitive species are used in Column III B.
[g] See Reference 9 for indication of type of models employed.
[h] Acceptable death rate should be defined and natural background levels should be considered; whereas TLV data usually consider physiological or behavioral effects, threshold limit in this case refers to genetic (carcinogenic, teratogenic, mutagenic, etc.) effects.

Figure 4. Sample multimedia environmental goals chart.

are based on the most sensitive applicable nonhuman species for which effects data are available. In Column IC, the estimated permissible ambient concentrations identified in either Column II, III, or IV are converted to emission level goals by multiplying the values in Column II, III, or IV by the dilution factor assumed for converting source concentrations to ambient concentrations. All media (air, water, land) are represented on the Chart to assure that attempts to control emissions to one medium do not result in increased adverse impact on others.

The goals derived from the MEG Chart will be used to assist in deciding what pollutants should receive emphasis in the EPA program, and in planning the control technology development program for FBC. It is re-emphasized that the MEG Chart is intended only for broad planning purposes; the limitations in available health/ecological effects data, and simplifications necessary in the models used for calculating some of the EPC are such that the entries in Columns III and IV cannot be taken as rigorous, absolute indicators of acceptable pollutant levels.

Further work on the MEG Chart is aimed at: (1) ultimately completing the chart for each substance on the UOPP list that—after preliminary screening and classifying—warrants further attention; and (2) deriving improved models for calculating EPC based on available health/ecological data. Available health/ecological effects data need to be collected, analyzed, and any differences reconciled, if possible. Modeling needs include, for example: improved methods of employing TLV, LD_{50} or other data to give air- and water-based EPC; and definition and quantification of the chains by which soil concentrations enter human and ecological systems, so that land-based EPC can be calculated. Attention will be given to estimating chronic pollutant effects, though much of the available data are for acute effects.

Comprehensive Analysis of Emissions (CA)

CA involves measuring emissions from operating FBC units to provide data for evaluating control technology needs. The CA program will be conducted in three staged levels, and is still in an evolutionary status. Level 1 CA involves comprehensive screening, using analytical techniques which sacrifice accuracy and compound specificity in order to identify possible problem areas in a cost effective manner. Level 2 is designed based upon Level 1; more accurate, compound-specific techniques are used to explore the identified problem areas. Level 3 includes routine monitoring of those pollutants identified as specific problems in Level 2. The types of tests conducted in Level 1 consisted of biological testing, as well as chemical analysis.

Available Control Technology Assessment

Assessment of the performance, cost, reliability, and environmental impact of applicable control technology is an essential step in identifying control technology needs. In practice the assessment of available technology and identification of further control technology development needs will be parallel efforts. Input data for technology assessment will be obtained from performance information on commercial devices, from engineering estimates, and from performance data obtained by CA on existing FBC units.

Environmental Alternatives Analysis (EAA)

EAA involves selection of the optimum combination of control options for a given process, taking into consideration (1) the "hazard" associated with the levels of each pollutant in each stream, and (2) the cost of alternative degrees of control. Further aims of EAA are to identify problem pollutants, and, based on degree of "hazard", (1) to rank effluent streams within a process, and (2) to compare individual processes or total plants.

To enable conduct of EAA, the primary tool currently under development is the Source Analysis Model (SAM). Basically, the SAM approach involves calculation of a normalized hazard factor for each pollutant in a selected stream by computing the ratio of the concentration of the pollutant in the stream to the goal concentration indicated in the MEG Chart; i.e.,

$$\text{hazard factor for pollutant } i \text{ in stream } k = \frac{C_{ik}}{(C_{ik})_{MEG}}$$

where C_{ik} is the observed concentration and $(C_{ik})_{MEG}$ is the emission goal read from Column IC or ID in the MEG chart for pollutant i. The total hazard factor for a stream can then be calculated by summing over all pollutants in the stream; the hazard factor for a plant can be calculated by summing all streams. If the performance of alternative individual control options for each stream is known, the SAM can be used to find the control option, or combination of options, which minimizes the hazard factor for any one stream or for the total plant.

Three versions of the SAM are under development by EPA's Industrial Environmental Research Laboratory/RTP, varying according to the level of detail in the model. These versions are:

- SAM/IA, to be used for initial rapid screening, using MEG goals based upon more readily available, acute toxicity data
- SAM/I, to be used for more rigorous screening, using MEG goals based upon chronic effect data
- SAM/II, a general model to be used for evaluating any U.S. regional site alternative.

Control Technology Development

A significant output of environmental assessment is the direction it will provide to the program of control technology development. The environmental alternatives analysis will compare the health/ecological effects goals, developed using the MEG Chart, with the observed results from comprehensive analyses and with the capabilities of current envisioned control options. If this analysis indicates that an unacceptable "hazard" exists for any pollutant, stream, or process variation, then a program must be designed to develop the control technology in order to reduce this hazard. Control technology development will proceed along the lines of five basic areas, as described earlier: input pretreatment; operating condition modification; design condition modification; add-on devices; and reduction of solid residue impact. However, at least three actual steps in the CTD process can be envisioned. These are:

Step 1 Characterization by EPA of control techniques and add-on control equipment existing on FBC units now operated by DOE and EPA; the characterization would also involve testing on existing units of mobile (trailer-mounted) control devices developed by EPA.

Step 2 Modification of techniques and devices by the EPA on the existing units to improve effectiveness as Step 1 may indicate.

Step 3 A long term program involving testing of advanced techniques and building of advanced control devices on FBC units to achieve the controls deemed necessary to meet ambient and emission level goals, demonstrating optimum multimedia control.

For the FBC process, these steps will begin in 1977 and run

Table III. Status summary of large scale FBC boilers.

Installation Name	Bed Size (m), Capacity, Type, Coal throughput (MTD)	Status
	Atmospheric Pressure Units	
Rivesville, WV	3 × 3.7, 30 MWe, Power generation, 326[a]	In shakedown; 3000 hr run by Spring 1978
Renfrew, Scotland	3 × 3, 15 MW_t, Steam, 30	Operating since 1975
Enkopings, Sweden	3.3 × 3.7, 25 MW_t, Heater, 45	Under construction, light off in 1978
Trichy, India	2 dia, 10 MW_t, PIB,[b] 22	Operating since June, 1976
MERC, WV	1.8 × 1.8, 6 MWe, CTIU,[c] 59	Under design
MIUS, Oak Ridge	1.8 × 1.8, 0.6 MWe, PDU,[d] 5.4	Under redesign, may operate in 1978
DOE-sponsored Units, USA	Various, Various, Industrial/Institutional, 27 to 907	All of them (6 to 8 units) are in design stages; may operate in 1979
EPRI-B&W, Alliance, OH	1.8 × 1.8, 10 MW_t, Steam generation, 22	Shakedown to be completed in Spring 1978
	Pressurized FBC Units	
BCURA, England	0.91 × 0.6, 2 MW_t, PDU, 4.5	In operation as experimental unit since 1970
Exxon Miniplant, NJ	0.3 dia, MW_t, PDU, 4.5	Has run 100 hrs continuously with regeneration and solids recirculation
Argonne National Laboratory	0.91 × 0.91, 2.4 to 9 MW_t, CTIU, 6 to 18	Under construction, to run in 1979
Combustion Power, Co., CA	2.1 dia, 1 MWe, PDU, 22	HTHP[e] particulate control and corrosion studies in progress on smaller unit
International Energy Agency, U.K.	2.0 × 2.0, 35 MWe, Power Generation, 326	In design stages
Bergbau-Forschung, W. Germany	3.7 dia, 3 MWe, Power Generation, 65	In design stages
Curtiss-Wright, NJ	3.7 dia, 13 MWe, Combined cycle, 109	Preliminary design stage, scheduled for 1980 operation.

[a] Divide these nominal feed rates by 24 to get metric tons (1000 kg)/hour actual feed rates; MTD = Metric tons per day.
[b] Packaged industrial boiler for steam generation.
[c] Component test and integration unit.
[d] Process development unit.
[e] HTHP = high temperature and high pressure.

through 1986, at about which time the erection of commercial FBC units is expected to gain real momentum.

Recommendation of Standards

One major product of the environmental assessment effort will be the development of a research data base adequate for recommending emission standards for atmospheric and pressurized FBC systems used in power generation or industrial steam generation. The research data base will include (1) emission-stream analysis data on large scale FBC units which constitute best current practice, including characterization of the available control technology; and (2) health/ecology-based (ambient-level-goals-related) emission level goals. If the best current practice indicates that near-term emission goals may not meet the goals dictated by H/E effects, continued development of control technology will be necessary. Therefore emission goals may have to be set for various time periods (for example 1985, 1995, and 2005) to ensure adequate incentive for FBC development in the near term, and adequate protection of health and ecology in the near and long term.

Preliminary experimental data indicate that both atmospheric and pressurized FBC systems can meet existing EPA emission standards for large conventional coal boilers for the gaseous criteria pollutants SO_2 and NO_x. Particulate control adequate to meet the EPA emission standard for conventional coal boilers has not been demonstrated, either for atmospheric or pressurized FBC. In the case of atmospheric systems, particulate control will likely be similar to that for a conventional boiler burning low sulfur coal; control at high temperature/pressure to meet conventional boiler emission standards for a pressurized FBC will require control technology which has not yet been demonstrated.

Emission data are being collected to develop a research data base suitable for recommending emission standards for fluidized bed coal boilers.

Status of FBC Technology Development

The major thrust of current FBC research worldwide is on the development of atmospheric boilers first. Currently, the largest atmospheric boiler is a 30 MWe unit installed at the Monongahela Power Company's Rivesville plant in West Virginia under ERDA sponsorship. The unit is in the start-up phase and 3000 hr demonstration runs are planned to begin within the next year, with concurrent comprehensive analysis of effluent streams. Another major AFBC unit is in Great Britain, the 45,000 lb steam/hr (20410 kb/hr, or 15 MW_t) steam generator at Renfrew, Scotland. Shown in Table III are several planned AFBC units. These include the Component Test and Integration Unit (CTIU) at Morgantown Energy Research Center (MERC), West Virginia, and a 25 MW steam generator for district heating by AB Enkopings at Varmavelk, Sweden. In India, a 20,000 lb steam/hr, or 9072 kg/hr (10 MW_t) packaged industrial boiler has been built at the Trichy Works of Bharat Heavy Electricals, Ltd., with the objective of obtaining commercial design data for construction of a packaged AFBC boiler. Also, recently the U.S. Department of Energy has initiated demonstration-scale programs for further development of AFBC aimed towards industrial steam-generation boilers and direct/indirect-fired heaters with eight different organizations. Finally, A–DOE is developing commercial AFBC plant designs. In addition to these relatively large boilers, about 20 experimental size AFBC units are being used in the U.S., England, Germany, and India.

About 10 pressurized (PFBC) units are planned or are in operation all over the world. The most significant of these are: (1) the Exxon Miniplant which uniquely features a combustor and sorbent regenerator with continuous recirculation of the sorbent; (2) the CTIU at Argonne National Laboratory planned for operation in late 1978, and a 6 in. (15.2cm) unit which has been in operation since 1970; (3) the process development unit (PDU) at Combustion Power Company; (4) the 30 MWe steam generation/steam turbine operation PFBC unit planned for the Grimethorpe Station in the United

Kingdom (sponsored by the International Energy Agency); (5) the 3 MWe unit for gas generation/gas turbine operation PFBC unit at Bergbau-Forschung, Essen, West Germany; and (6) the 13 MWe pilot plant at Curtiss-Wright Company in New Jersey. A status summary of the major atmospheric and pressurized FBC units is presented in Table III.

Resource Conservation with FBC

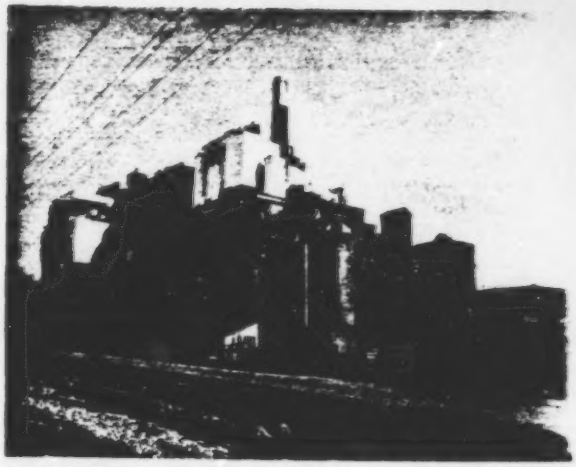
FBC offers several conservation features:

- Fluidized-bed combustion boilers can burn any fuel, including low grade lignite and gasification residues (chars), to produce steam or electricity. This aspect will permit the use of otherwise hard to utilize sources of energy and thus extend the energy resources of the nation.
- Estimates show that pressurized FBC with combined cycle power generation can have an overall thermal efficiency of up to 42% compared with 34% for conventional coal-fired power plants using wet scrubbing and stack gas reheat. The resulting reduction of 19% in heat rate can save several million tons of coal per year, and hence can reduce environmental impact. This estimate assumes that the PFBC process will be successfully commercialized to provide at least 10% of the boiler market in the 1990's.
- Successful development of the modular integrated utility system (MIUS) concept and packaged industrial FBC boilers could significantly reduce the use of natural gas and petroleum liquids as sources of heat energy, thereby conserving these higher quality fuels as industrial raw materials for future generations.
- Experimental evidence indicates that NO_x emissions from FBC units (0.2–0.6 lb/10^6 Btu, or 0.09–0.26 g/10^6J) are below the current EPA New Source Performance Standard of 0.7 lb/10^6 Btu (0.30 g/10^6J) for large coal-fired conventional boilers; thus significant amounts of energy may be saved by avoiding the use of some energy-intensive combustion modification techniques for NO_x control which may be necessary for some conventional coal boilers, depending upon the level at which any NO_x standard for FBC is set.
- The lower temperature of the fluidized bed and improved bed and heat transfer designs now under way suggest that tube life in FBC could be significantly extended, thus slowing the rate of raw materials consumed in boiler-tube manufacture. Also, FBC boilers will be smaller in size due to improved heat transfer characteristics.
- The elimination of the wet scrubbing requirements by the in-bed removal of SO_2 with limestone or dolomite sorbents constitutes a water resource conservation measure which is particularly suitable for dry areas in the U.S.

The projected increase in U.S. energy consumption makes it necessary to encourage conservation by selecting the lesser energy-intensive process not only for power generation but for all industrial processes. FBC appears to provide an alternative to the more energy-intensive, conventional coal-fired power plants with add-on pollution controls.

Summary

The fluidized-bed combustion process appears to be an environmentally promising alternative for utilizing coal as well as a wide range of fossil fuels for power and steam generation. Environmental assessment of the process, and development of necessary control technology are under way in parallel with the national program to develop the process.



New technology in an old building. Designed, built and operated by Pope, Evans and Robbins Incorporated, atmospheric fluidized-bed boiler installation at Monongahela Power Company, Rivesville, WV, has 30 MW capacity. Electrostatic precipitator serving new installation is seen at near corner of 40 year old facility.

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